Insertion, Validation, and Application of Barotropic and Baroclinic Tides in 1/12 and 1/25 Degree Global HYCOM

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LONG-TERM GOALS

A partnership of institutions (academia and government) is collaboring on inserting and validating barotropic and baroclinic tides in 1/12° and 1/25° numerical simulations of the global ocean. The collaboration will also apply the results of the 1/12° and 1/25° simulations to a number of problems of scientific interest, described in further detail below. This partnership builds on the strong relationship that the lead PI of this proposal, Brian Arbic, has established since 2006 with the Naval Research Laboratory (NRL) and Florida State University (FSU). NRL and FSU have a long-standing relationship, developed during the National Oceanographic Partnership Program (NOPP)-supported HYCOM (HYbrid Coordinate Ocean Model) consortium effort, to develop and transition an eddy-resolving, real-time global and basin-scale ocean prediction system. These systems have been or are in the process of being transitioned for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS. This project builds upon work begun with Naval Research Laboratory contract N000173-06-2-C003, and reported on in Arbic et al. (2010).

OBJECTIVES

The partnership will utilize global HYCOM, run at horizontal resolutions of 1/12° and 1/25°, with barotropic and baroclinic tides inserted. Thus far, the global NRL simulation is a forward simulation; that is, a simulation without data assimilation. The NRL group is working to develop accurate data-assimilative models with tides. The contribution of the University of Michigan (UM) group to the assimilation effort will be to recruit a graduate student to work with Arbic and NRL collaborators on this topic. Since the goal of operational models is high accuracy, we have endeavored to create forward models which achieve a high level of accuracy in the tides before the data assimilation is inserted. In this way, the data-assimilative models build upon an accurate foundation laid by the forward models. Our research will continue to focus on improving the forward tidal simulations, with an added new focus on building up a new capacity for data-assimilative simulations which include tides. In addition, Arbic and the UM team will collaborate with both NRL and FSU on the most efficient way to store HYCOM output with tides in the FSU-based data server.

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As an important first step in improving the forward tide model, the horizontal resolution of HYCOM simulations containing eddies and tides simultaneously has recently been increased to 1/25°. New simulations at this resolution are already running on DoD machines. The higher resolution simulations are in line with stated U.S. Navy goals to have a 1/25° resolution version of the HYCOM ocean prediction system, with tides, available in the near future for Navy operational purposes. The topographic wave drag scheme utilized in the model will be improved through use of the statistical roughness field produced in a separate Office of Naval Research (ONR) grant (John Goff and Brian Arbic, N00014-07-1-0792 and N00014-09-1-1003, "Effects of small-scale bathymetric roughness on the global internal wave field"; Goff and Arbic 2010). As shown by a number of authors, topographic wave drag is critical to the accuracy of forward tide models. In addition, scientific applications of the wind-plus-tides simulations will be investigated during the course of this proposed research. For instance, the three-dimensional global tidal velocity and isopycnal displacement field in HYCOM will be compared to that measured by current meters. The sea surface height signatures of internal tides in HYCOM will be validated globally against satellite altimeter measurements. The temporal stability of the internal tide signals at the surface in the face of mesoscale activity will be examined. The impact of tides on sea surface height spectra will be examined, with implications for the development of the proposed wide-swath satellite altimeter (NASA SWOT mission). Three-dimensional maps of internal-wave driven energy dissipation and mixing will be developed from the HYCOM simulations. Parametric subharmonic instability in the model will be examined, as will interactions between tides and low-frequency motions. We already have preliminary results on some of these topics and we will show some of our preliminary results here. Finally, Arbic and his team at UM will collaborate with NRL on the introduction and validation of data assimilation into the HYCOM tide simulations, and with both NRL and FSU on the FSU-based HYCOM data server. Regarding the latter point, we will specifically examine how to optimize the storage of HYCOM output on the server at high spatial resolution (1/25° global) when tides are included, which traditionally leads to much higher temporal sampling than is done in models which do not include tides.

APPROACH

We insert tides into HYCOM following the techniques outlined in Arbic et al. (2004), which can be consulted for extensive discussions on global tide modeling. The astronomical tidal potentials of the eight largest tidal constituents, adjusted for the effects of solid-earth body tides (e.g., Hendershott 1972) were entered into the momentum equations. For our first simulations self-attraction and loading (Hendershott 1972, Ray 1998) is parameterized using the simple scalar approximation (Ray 1998). Topographic wave drag, which represents energy loss due to breaking of internal waves generated by tidal flows over rough topography, is also inserted into the model momentum equations. This has been common practice for forward tide models since the pioneering effort of Jayne and St. Laurent (2001). With the drag scheme incorporated, HYCOM captures about 92% of the sea surface elevation variance of the eight largest tidal constituents as measured by a standard set of 102 pelagic tide gauges (Shum et al. 1997). This level of accuracy for the barotropic tides is comparable to that seen in previous carefully tuned forward tide models, e.g. Arbic et al. (2004).

The key individuals involved in this research are:

--Brian K. Arbic, University of Michigan, PI of this grant: Arbic is in frequent contact with the individuals listed below as we continue to research tides in HYCOM. Arbic is also currently working

with Malte Mueller and Maik Thomas to improve the astronomical tidal forcing implementation in HYCOM, and will focus next summer on improving the topographic wave drag utilized in HYCOM.

--Patrick G. Timko, University of Michigan, postdoc supported by this grant: Timko is validating the three-dimensional structure of tidal currents and displacements in HYCOM with respect to the current meter observation archive of Scott et al. (2010).

 --Graduate student funded off of this grant and to be determined, University of Michigan: The graduate student will collaborate with Arbic and NRL researchers on incorporating data assimilation into the HYCOM-with-tides simulations. To recruit this student, Arbic is visiting five midwestern liberal arts colleges this academic year, putting advertisements into Physics Today, AGU EOS Transactions, and the UK Meteorology jobs list, giving talks at three forums within UM, posting the position on the Arbic group website, and sending "dear friends" letters to colleagues.

--Eric P. Chassignet, Florida State University, head of HYCOM consortium and keeper of the HYCOM data server: As discussed above and below, we will work with Chassignet on the storage strategy for the server.

--Alan J. Wallcraft, NRL Stennis Space Center, lead PI of related tides grant at NRL: Wallcraft and Arbic collaborated to insert tides into the HYCOM code and continue to consult each other about the technical aspects of the tide coding.

--E. Joseph Metzger, NRL Stennis Space Center: Metzger continues to generally be the NRL go-to person for running the HYCOM simulations.

--Jay F. Shriver, NRL Stennis Space Center: Shriver is performing global comparisons of HYCOM to the satellite altimeter data of Richard Ray, and following upon this will examine the temporal stationarity of internal tides. These are both topics of great interest to NASA as it prepares for the wide-swath satellite altimeter.

--James G. Richman, NRL Stennis Space Center: Richman is an active contributor to Timko's and Shriver's projects, and is taking the lead on examining the impact of internal tides on the wavenumber spectra of sea surface height, a subject also of great interest to NASA.

WORK COMPLETED

HYCOM has been run globally with tides at 1/12° resolution, and a 1/25° global tidal simulation is currently being performed. Numerous analyses have been performed on the 1/12° simulations. The most significant results obtained during the last year are described in the following section.

RESULTS

The most interesting results from this past year have been obtained by Shriver and Richman, Arbic's NRL collaborators, and by Timko, Arbic's postdoc. Shriver has harmonically analyzed one year of output from the HYCOM-with-tides simulations and high-passed the resulting tidal amplitudes to reveal the signature of internal tides at the sea surface. Figure 1 below, taken from Shriver et al. (2011), displays the amplitude of the M_2 signature in both altimeter data (top panel; Ray and Mitchum

1996, 1997; Ray and Byrne 2010) and HYCOM (bottom panel). The figures demonstrate that HYCOM is capturing the hotspots of internal tide generation well. Shriver et al. (2011) confirms this by showing that the HYCOM RMS amplitudes over the hotspot boxes shown in Figure 1 are within about 20% of those in altimeter data for the most important constituents (results not shown here for the sake of brevity). In the HYCOM K_1 results (not shown), there are no internal waves poleward of 30°, as expected from theoretical considerations. The altimeter results contain substantial K_1 activity in western boundary currents poleward of 30°. We interpret this as mesoscale contamination brought about by the relatively poor temporal sampling of the altimeter; the 10 day repeat time of the altimeter aliases tides into the mesoscale band. The K_1 comparison shows that the hourly sampling possible in HYCOM can yield important limitations in the altimeter data.
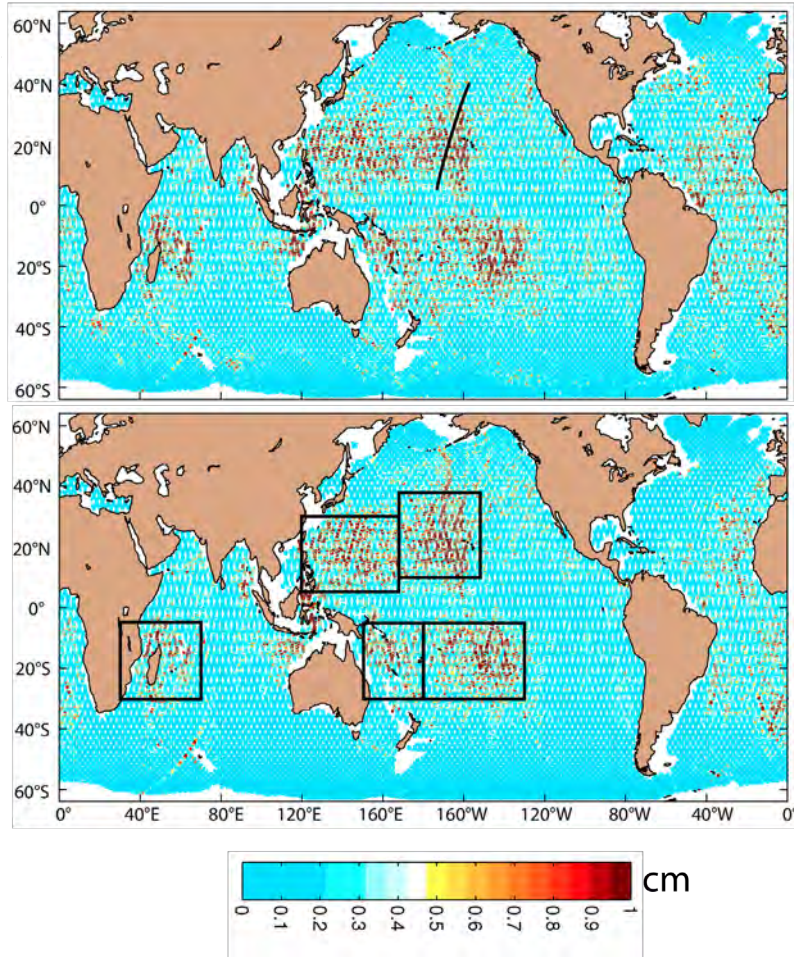

Figure 1: Amplitude (cm) of M₂ internal tide signature in sea surface height, obtained from high-passing the M₂ amplitudes of the full sea surface height. Upper panel: results from satellite altimeter. Lower panel: results from HYCOM.

Richman has also taken advantage of the hourly output of HYCOM, to separate the contributions of low and high frequencies to the wavenumber spectrum of sea surface height. In regions of low internal

tide activity, the low frequencies dominate the spectrum (not shown). However, in regions of high internal tide activity, the high frequencies dominate the spectrum, as shown in Figure 2. The implications are that the low-frequency spectrum, which is predicted by surface quasi-geostrophic theory to have a slope of -11/3 (Le Traon et al., 2008), will be buried underneath the high frequency spectrum in regions of high internal tide activity. Therefore, the internal tide corrections to the wide-swath satellite altimeter data will have to be very accurate to reveal submesoscale dynamics in regions of high internal tide activity. Richman is currently preparing a paper on these results.

Timko has compared the global three-dimensional tidal velocity field in HYCOM with available current meter data (Timko et al. 2011a, 2011b), and will soon undertake a comparison of the global three-dimensional tidal displacement field in HYCOM with available current meter data. Timko et al. (2011a) finds that the semi-diurnal tidal currents in HYCOM match up with those in current meter data reasonably well, as long as substantial averaging is done over both time and space. Timko et al. (2011b) develops rigorous criteria for model/data comparisons at individual current meter locations. In general, the diurnal currents in HYCOM are too weak in comparison to observations. This result inspired us to revisit our topographic wave drag. The drag is tuned for M_2, which results in a drag that is probably too strong for K_1. We are currently engineering the wave drag so that it is weaker for K_1 than it is for M_2, in accordance with theoretical considerations (Bell 1975). Figure 3 shows a model/data comparison in a North Pacific location where the model performs particularly well.
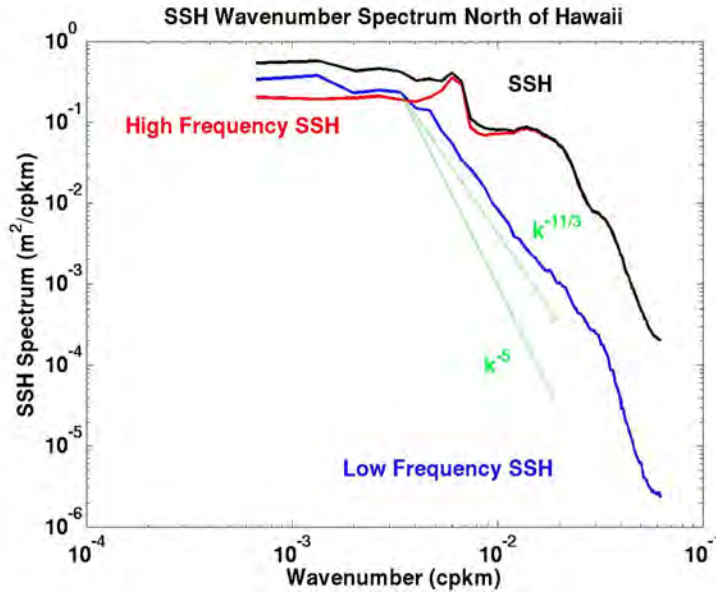

Figure 2: Wavenumber spectrum of steric sea surface height in region of high internal tide activity near Hawai'i. Black/blue/red curves represent spectra of steric height, low frequency steric height, and high frequency steric height, respectively. Extra slanted lines are at theoretically predicted slopes of -11/3 and -5.
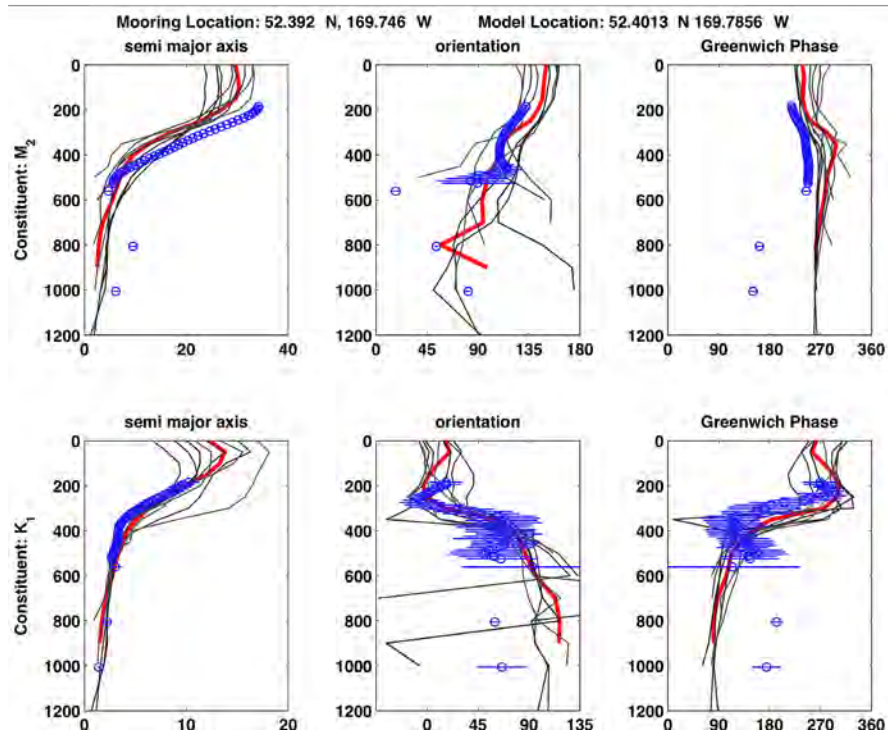
Figure 3: Vertical structure of tidal currents in ADCP data (blue curves), nearest model gridpoint in HYCOM (red curves), and in eight surrounding model gridpoints (black curves). Top/bottom panels are for M_2 / K_1, respectively. Left/middle/right panels show semi-major axis, orientation, and Greenwich phase, respectively.

IMPACT/APPLICATIONS

The tidal research is driven by the stated need for NAVOCEANO to have tides and data assimilation in 1/25 degree HYCOM, for operational purposes.

The wavenumber spectrum calculation done by Richman was done at the request of the wide-swath satellite altimeter PIs (Lee-Lueng Fu, Rosemary Morrow, Ernesto Rodriguez), who have invited Arbic to several planning meetings for the wide-swath altimeter. Shriver's results have been shown at these planning meetings and have garnered great interest.

TRANSITIONS

The work reported on here is an important part of a planned transition by the Stennis Space Center ocean modeling group from forecasts that are based on NLOM (Naval Research Laboratory Layered Ocean Model) to HYCOM. Tides are among a number of improvements in the HYCOM simulations compared to the NLOM simulations.

RELATED PROJECTS

The work reported on here is strongly tied to the HYCOM tides grants currently in place at Florida State University (led by Eric Chassignet) and at Naval Research Laboratory (led by Alan Wallcraft). Arbic has been working closely with Wallcraft and other NRL Stennis personnel (Metzger, Richman, Shriver) since 2006 to implement and validate tides in HYCOM. Arbic has continued to work closely with Stennis personnel as the papers listed below under "Publications thus far, resulting from current grant" have been recently submitted. More studies and papers are planned, and the close collaborations will continue. Arbic will work closely with NRL collaborators and with Chassignet to decide how best to store simulations with tides included on Florida State's data server. Tidal data is traditionally stored hourly, but hourly three-dimensional global output from HYCOM will likely overwhelm any server at Florida State. As we have been doing with the simulations thus far, we will decide on sampling strategies to best handle this problem. Thus far, for instance, we have been saving 1) daily averages of three-dimensional global output, 2) three-dimensional global output at hourly intervals over the timespan of one month, 3) selected variables, such as sea surface height and surface velocities, at hourly intervals over several years, 4) selected regions of interest, such as Hawai'i and the Philippines, at hourly intervals and at full three-dimensional spatial resolution. We will discuss similar strategies for the Florida State data server.

The work reported on here was leveraged to obtain two grants from NSF, both involving multiple institutions. The focus of one NSF grant is to examine the impact of bottom boundary layer drag and topographic wave drag on low-frequency motions such as mesoscale eddies and western boundary currents. The postdoc employed on this grant, David Trossman, has obtained computer accounts on NAVO and ERDC machines, and is working closely with Joe Metzger and Alan Wallcraft. We expect the wave drag to impact the model energy budgets, and perhaps the model dynamics, significantly. This work should therefore be beneficial for the HYCOM project. The other NSF grant is a Climate Process Team (CPT) grant led by Jennifer MacKinnon and focused on developing better parameterizations of internal-wave driven mixing for ocean models. This project involves many internal wave experts (Polzin, St. Laurent, Alford, Simmons, Kunze, Gregg, MacKinnon, Legg, Klymak, Pinkel), most of whom work on Navy-funded internal wave projects. One of the four postdocs funded by this CPT, Joseph Ansong, is based at UM and is analyzing the HYCOM with tides simulations reported on here for the NSF work. Specifically he is examining parametric subharmonic instability in the model (Simmons 2008), and will be computing barotropic-to-baroclinic energy conversions as in Simmons et al. (2004), but under more realistic conditions such as the prsence of eddies and of horizontally varying stratification. Ansong has already visited Simmons in order to facilitate better communication, and is planning to visit Alford and Gregg later in the fall. The results of Ansong's NSF-funded research, like those of Trossman's, are anticipated to be beneficial to the HYCOM-with-tides project reported on here.

Two additional brief notes of interest: First, as anticipated, Patrick Timko, who is funded by this ONR grant, was instrumental in helping to get Trossman and Ansong up to speed on their NSF-funded HYCOM projects. Second, since Ansong is from sub-Saharan Africa, he represents a member of an under-represented group working on HYCOM. However, since he is funded by an NSF grant, I did not count him as a minority postdoc working on this ONR grant.

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Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2011b: Skill tests of three-dimensional tidal currents in a global ocean model, submitted.

PUBLICATIONS THUS FAR, RESULTING FROM CURRENT GRANT

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft, and P.G. Timko, 2011: Comparison of internal tides in a high resolution global ocean circulation model with altimetric estimates, in revision.

Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2011a: Comparison of tidal kinetic energy in a global three-dimensional circulation model, historical current meter observations, and a global barotropic model, in revision.

Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2011b: Skill tests of three-dimensional tidal currents in a global ocean model, submitted.